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Relaxed fine-tuning in models with non-universal gaugino masses

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Abstract

We study, in a bottom-up approach, the fine-tuning problem between soft SUSY breaking parameters and the μ-term for the successful electroweak symmetry breaking in the minimal supersymmetric standard model. It is shown that certain nontrivial ratios between gaugino masses, that is non-universal gaugino masses, are necessary at the GUT scale, in order for the fine-tuning to be reduced above 10 % order. In addition, when all the gaugino masses should be regarded as independent ones in their origins, a small gluino mass $M_3 \lesssim 120$ GeV and a non-vanishing A-term $A_t \sim O(M_3)$ associated to top squarks are also required at the GUT scale as well as the non-universality. On the other hand, when we consider some UV theory, which fixes ratios of soft SUSY breaking parameters as certain values with the overall magnitude, heavier spectra are allowed. It is favored that the gluino and wino masses are almost degenerate at the weak scale, while wider region of bino mass is favorable.

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1 Introduction

Supersymmetric extension of the standard model (SM) is one of the most promising candidates for a new physics at the TeV scale. It can stabilize the huge hierarchy between the electroweak (EW) scale and the Planck scale. In particular, the minimal supersymmetric standard model (MSSM) is interesting from the viewpoint of its minimality. Also the MSSM unifies three gauge couplings of SM gauge interactions at the grand unified theory (GUT) scale $M_{GUT} \sim 2 \times 10^{16}$ more precisely. Furthermore, supersymmetric standard models provide sources for the dark matter.

Among such attractive features, the most remarkable one would be the radiative EW symmetry breaking [1]. The MSSM can automatically break EW symmetry due to the large logarithmic correction to the soft supersymmetry (SUSY) breaking mass m_{H_u} for the up-sector Higgs field [2],

$$\Delta m_{H_u}^2 \quad \sim \quad -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln \frac{\Lambda}{m_{\tilde{t}}},$$

which determines the size of Z-boson mass M_Z as

$$\frac{1}{2} M_Z^2 \quad \sim \quad -\mu^2 - m_{H_u}^2,$$

through a minimization condition for the Higgs potential. Here, y_t is the top Yukawa coupling, $m_{\tilde{t}}$ is the top squark mass, Λ is the cut-off scale, and μ is the SUSY mass of up- and down-sector Higgs fields. We have assumed a (moderately) large value of $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$.

On the other hand, the MSSM predicts the lightest CP-even Higgs mass at one-loop level,

$$m_h^2 \quad \leq \quad M_z^2 + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\tilde{t}^2}}{m_t^2} + \cdots.$$

The experimental bound $m_h \geq 114.4$ GeV requires $m_{\tilde{t}} \gtrsim 500$ GeV. This value of $m_{\tilde{t}}$ leads to quite large correction $\Delta m_{H_u}^2$. Thus, to obtain M_Z, we need typically a few percent fine-tuning between the SUSY mass μ and the soft SUSY breaking mass m_{H_u} at the GUT scale, which are not related to each other in general. This is sometimes called a 'little hierarchy problem' [3]. There have been several works recently addressing this issue [4]-[15]. Most of them, however, are based on some specific models.

Here, we study the fine-tuning problem from the bottom-up viewpoint, and show what kind of model can relax this sort of fine-tuning. We will take two kinds of stances. One is a complete bottom-up approach, where all the soft SUSY breaking parameters are considered as independent ones to each other in their origins. In this case, we have to care about the sensitivity of the EW scale (Z-boson mass) to all the parameters at the GUT scale. The other is, in a sense, a half top-down approach. We suppose some ultra-violet (UV) theories which fix certain ratios between the soft parameters at the GUT scale. Then we consider the fine-tuning between the remaining independent ones. We will show preferable values of the ratios between gaugino masses and the A-term.

Indeed, several models lead to non-universal gaugino masses as well as non-universal scalar masses and A-terms, e.g. moduli mediation [16], anomaly mediation [17], mirage mediation [18, 9] and the SUSY breaking scenario, where F-components of gauge non-singlets are dominant [15, 19]. (See also Ref. [20] for several classes of models leading to non-universal gaugino masses with certain ratios.) Scalar masses and A-terms are more model-dependent. However, in each model, ratios of gaugino masses and scalar masses as well as A-terms are fixed as certain values. In these models, the independent parameter for SUSY breaking terms corresponds to the overall magnitude of SUSY breaking, say M, and we should concentrate to only the fine-tuning of the overall magnitude M.

The sections of this paper are organized as follows. In Section 2, we briefly review the fine-tuning problem in the MSSM, and introduce fine-tuning parameters. In Section 3, we discuss how the fine-tuning can be reduced when all the soft SUSY breaking parameters are regarded as independent ones. In Section 4, on the other hand, we examine the fine-tuning problem under the assumption that certain ratios between soft parameters, especially between gaugino masses, are fixed by some UV theories and find preferable ratios which reduce the fine-tuning. Section 5 is devoted to conclusions and discussions.

2 Fine-tuning problem in MSSM

In this section we review the fine-tuning problem in the MSSM shortly, and then introduce fine-tuning parameters describing the sensitivity of the EW sale to the soft parameters at the GUT scale.

The MSSM Higgs sector is described by the superpotential,

$$W_{SUSY} = \mu H_u H_d + y_t Q_3 U_3 H_u,$$

and the relevant soft SUSY breaking terms are written as,

$$V_{\rm solf} = m_{Hu}^2|H_u|^2 + m_{Hd}^2|H_d|^2 + m_{Q_3}^2 + m_{U_3}^2 + (\mu B H_u H_d + y_t A_t Q_3 U_3 H_u + {\rm h.c.}),$$

where m_{H_d}, m_{Q_3} and m_{U_3} are the soft scalar mass for H_d, Q_3 and U_3, respectively, μB is the SUSY breaking mass (μB-term) between H_u and H_d, and A_t is the scalar trilinear coupling (A-term) involving the top squarks. Throughout this paper, we neglect all the Yukawa couplings and the A-terms except for ones associated to the top quark supermultiplets, y_t and A_t. Note that we use the same notation for denoting a chiral superfield and its lowest scalar component.

The EW symmetry breaking causes the Z-boson mass $M_Z = 91.2$ GeV. A minimization condition of the total Higgs potential results in the following relation,

$$\begin{aligned} \frac{1}{2}M_Z^2 &= -\mu^2(M_Z) - \frac{m_{Hu}^2(M_Z)\tan^2\beta - m_{H_d}^2(M_Z)}{\tan^2\beta - 1} \\ &\sim -\mu^2(M_Z) - m_{Hu}^2(M_Z), \end{aligned} \tag{1}$$

where and hereafter we assume a (moderately) large value of $\tan\beta = \langle H_u\rangle/\langle H_d\rangle$ like $\tan\beta \gtrsim 5$. The radiative correction to $m_{H_u}^2$ is dominantly given by the contributions from

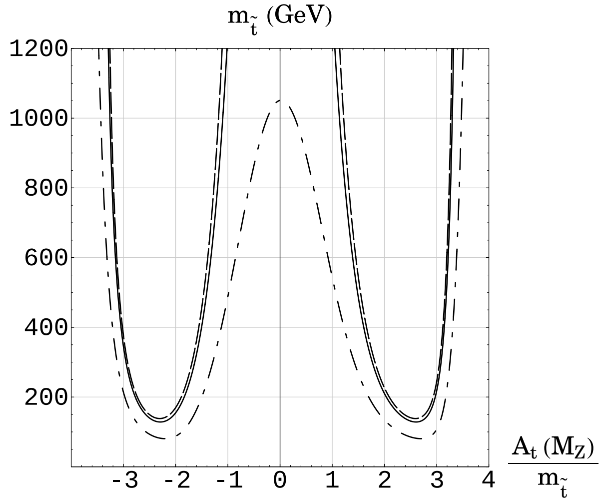


Figure 1: The lower bound on the averaged top squark mass $m_{\tilde{t}}$ for $m_h \geq 114.4$ GeV (solid line) as well as $m_h \geq 110$ GeV (dot-dashed line) and $m_h \geq 115$ GeV (dashed line). The other parameters are chosen as $m_t = 164.5$ GeV, $\mu = 200$ GeV and $\tan\beta = 10$.

top squarks with mass scale $m_{\tilde{t}}$, which is estimated as

$$\Delta m_{H_u}^2(M_Z) \approx -\frac{3y_t^2(M_Z)}{4\pi^2} m_{\tilde{t}}^2 \ln\frac{\Lambda}{m_{\tilde{t}}}. \tag{2}$$

On the other hand, within the two-loop approximation the lightest Higgs boson mass is constrained by [21]

$$\begin{aligned} m_h^2 \leq\ & M_z^2 \cos^2 2\beta \Big(1 - \frac{3m_t^2}{8\pi^2 v^2} \ln\frac{m_{\tilde{t}}^2}{m_t^2}\Big) \\ & + \frac{3m_t^4}{4\pi^2 v^2}\Big[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{\tilde{A}_t^2}{m_{\tilde{t}}^2}\Big(1 - \frac{\tilde{A}_t^2}{12 m_{\tilde{t}}^2}\Big) \\ & + \frac{1}{16\pi^2}\Big(\frac{3m_t^2}{2v^2} - 32\pi\alpha_3\Big)\Big\{\frac{2\tilde{A}_t^2}{m_{\tilde{t}}^2}\Big(1 - \frac{\tilde{A}_t^2}{12 m_{\tilde{t}}^2}\Big)\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \Big(\ln\frac{m_{\tilde{t}}^2}{m_t^2}\Big)^2\Big\}\Big], \end{aligned} \tag{3}$$

where $\tilde{A}_t = A_t(M_Z) - \mu\cot\beta \approx A_t(M_Z)$ and $m_{\tilde{t}}$ is the averaged top squark mass,

$$m_{\tilde{t}}^2 = \sqrt{m_{Q_3}^2(M_Z)\, m_{U_3}^2(M_Z)}. \tag{4}$$

The strong gauge coupling g_3, the vacuum value of the lightest Higgs field v, and the running top quark mass m_t at the M_Z scale are given by $\alpha_3(M_Z) = g_3^2/4\pi \approx 0.12$, $v = 173.7$ GeV, and $m_t = 164.5$ GeV, respectively.

From the two-loop expression (3) and the observed lower bound by the LEP experiment $m_h^2 \geq 114.4$ GeV, we can estimate the allowed lowest value of the top squark mass which is shown in Fig. 1. From this figure it is apparent that a relatively large A-term at the EW scale

$$|A_t(M_Z)/m_{\tilde{t}}| \gtrsim O(1),$$

is favorable for the Higgs boson mass above the LEP bound. Furthermore, for a small value of $|A_t(M_Z)/m_{\tilde{t}}|$, a considerably large top squark mass is required as

$$\begin{aligned} m_{\tilde{t}} &\gtrsim 500 \text{ GeV}, \qquad \text{for } |A_t(M_Z)/m_{\tilde{t}}| \lesssim 1.5, \\ m_{\tilde{t}} &\gtrsim 1000 \text{ GeV}, \qquad \text{for } |A_t(M_Z)/m_{\tilde{t}}| \lesssim 1.0. \end{aligned} \tag{5}$$

This large top squark mass causes $m^2_{Hu}(M_Z)$ in Eq. (1) to be much larger than $O(M_Z^2)$, because of the one-loop effect (2) with a large logarithm. Thus, μ^2 must be fine-tuned in order to obtain the successful EW breaking with $M_Z \sim 91.2$ GeV. This is the so-called little hierarchy problem.

The expressions (1), (2) and (3) are all written in terms of the low energy values of parameters such as $m^2_{H_u}(M_Z)$ and $m^2_{\tilde{t}}$. We express the soft parameters at the EW scale in terms of ones at the GUT scale [22], by integrating the one-loop renormalization group equations [1]. For example, the gaugino masses at the EW scale are written in terms of themselves at the GUT scale as

$$\begin{aligned} M_1(M_z) &= 0.41 M_1, \\ M_2(M_z) &= 0.82 M_2, \\ M_3(M_z) &= 2.91 M_3. \end{aligned} \tag{6}$$

On the other hand, the scalar masses m_{H_u}, m_{Q_3}, m_{U_3} and A_t at the EW scale are given by

$$\begin{aligned} -2m^2_{Hu}(M_z) &= 5.45M_3^2 + 0.0677M_3M_1 - 0.00975M_1^2 \\ &\quad +0.470M_2M_3 + 0.0135M_1M_2 - 0.433M_2^2 \\ &\quad +0.773A_tM_3 + 0.168A_tM_2 + 0.0271A_tM_1 \\ &\quad +0.214A_t^2 - 1.31m^2_{Hu} + 0.690m^2_{Q_3} + 0.690m^2_{U_3}, \end{aligned} \tag{7}$$

$$\begin{aligned} m^2_{Q_3}(M_Z) &= 5.76M_3^2 - 0.0113M_1M_3 - 0.00679M_1^2 \\ &\quad -0.0782M_2M_3 - 0.00225M_1M_2 + 0.400M_2^2 \\ &\quad -0.129A_tM_3 + 0.0281A_tM_2 + 0.00451A_tM_1 \\ &\quad -0.0357A_t^2 - 0.115m^2_{H_u} + 0.885m^2_{Q_3} - 0.115m^2_{U_3}, \end{aligned} \tag{8}$$

$$\begin{aligned} m^2_{U_3}(M_Z) &= 4.85M_3^2 - 0.0226M_1M_3 + 0.0453M_1^2 \\ &\quad -0.156M_2M_3 - 0.00451M_1M_2 - 0.183M_2^2 \\ &\quad -0.258A_tM_3 + 0.0561A_tM_2 + 0.00903A_tM_1 \\ &\quad -0.0713A_t^2 - 0.230m^2_{H_u} - 0.230m^2_{Q_3} + 0.770m^2_{U_3}, \end{aligned} \tag{9}$$

$$A_t(M_Z) = 2.16M_3 + 0.268M_2 + 0.0340M_1 + 0.310A_t. \tag{10}$$

Here the soft parameters without an argument in the right-hand side stand for the values at the GUT scale. We impose the boundary conditions $5\alpha_1/3 = \alpha_2 = \alpha_3 = 1/24$ at the

GUT scale $M_{GUT} = 2 \times 10^{-16}$ GeV and $y_t(M_Z) = m_t/v$ at M_Z. The μ-parameter receives a small radiative correction, and is shown to be

$$\mu^2(M_Z) \;=\; 1.09\mu^2. \tag{11}$$

The large contribution to the Higgs soft mass (2) from top squarks is now translated into the gluino mass squared M_3^2 with the largest coefficient 5.45 in Eq. (7). The mass squared M_3^2 also appears in $m_{Q_3}^2(M_Z)$ and $m_{U_3}^2(M_Z)$ in Eqs. (8) and (9), respectively, as dominant terms. From Eqs. (4), (8) and (9), if all the soft parameters take similar values, i.e., $M_a \approx m_i \approx A_t$ $(a = 1, 2, 3)$, we find

$$m_{\tilde{t}}^2 \;\approx\; 5M_3^2. \tag{12}$$

From Eqs. (5) and (12), the lower bound for M_3 is estimated as

$$\begin{aligned} M_3 &\gtrsim 220 \text{ GeV}, \qquad \text{for } |A_t(M_Z)/m_{\tilde{t}}| \lesssim 1.5, \\ M_3 &\gtrsim 450 \text{ GeV}, \qquad \text{for } |A_t(M_Z)/m_{\tilde{t}}| \lesssim 1.0, \end{aligned} \tag{13}$$

in order to satisfy the Higgs mass bound (3). Thus M_3^2 term with the large coefficient in Eq. (7) and then in Eq. (1) is much larger than M_Z^2. The other terms such as μ in the right-hand side of Eq. (1) must cancel this large contribution with a good accuracy in order to yield the correct Z-boson mass.

From Eq. (7), we also find that this fine-tuning of μ becomes more severe if we have non-vanishing positive values of $m_{Q_3}^2$ and $m_{U_3}^2$ at the GUT scale.[1] Then, as far as the little hierarchy problem is concerned, it is better that the model has vanishing top squark soft masses at the GUT scale,

$$m_{Q_3}^2 \;=\; m_{U_3}^2 \;=\; 0, \tag{14}$$

and we adopt this condition in the following analysis.

On the other hand, the Higgs soft mass squared at the GUT scale, $m_{H_u}^2$, appears in Eq. (7) with a positive coefficient of $O(1)$ and then negative in Eq. (1). Thus, $m_{H_u}^2 \sim O(M_3^2)$ can reduce the fine-tuning. We can approximately 'renormalize' this contribution into the μ-parameter effectively of Eqs. (1) and (11), i.e.,

$$-1.09\mu^2 \;\longrightarrow\; -1.09\mu^2 - 0.66m_{H_u}^2, \tag{15}$$

in the following discussion of the fine-tuning, because the $m_{H_u}^2$-terms are negligible in Eqs. (8) and (9) due to the suppressed coefficients of $O(0.1)$. We can easily separate this effect from the effective μ-parameter, if necessary. Then, first we just set

$$m_{H_u}^2 \;=\; 0, \tag{16}$$

in the expressions, and consider the μ-term is the effective one when we evaluate an effect due to a non-vanishing value of $m_{H_u}^2$ at the GUT scale.

[1] We can think of introducing tachyonic squarks at the GUT scale, i.e., $m_{Q_3}^2$, $m_{U_3}^2 < 0$, which can reduce the fine-tuning as is also indicated from Eq. (7). Such possibility has been studied in Ref. [14]. In this paper, we study the fine-tuning problem without the tachyonic boundary conditions at the GUT scale.

Based on these arguments, we focus on the contributions from M_a, A_t and μ in Eqs. (7), (8) and (9) in the following analysis. Then, we introduce fine-tuning parameters,

$$\Delta_X \;=\; \frac{1}{2}\frac{X}{M_Z^2}\frac{\partial M_Z^2}{\partial X}, \qquad (X = \mu,\, M_1,\, M_2,\, M_3,\, A_t). \tag{17}$$

We can easily check that these parameters satisfy the relation,

$$\sum_X \Delta_X \;=\; 1, \tag{18}$$

and then $\Delta_X \sim O(1)$ implies that the Z-boson mass is insensitive to the parameter X (at the GUT scale). The degree of fine-tuning for the parameter X can be considered as $100/\Delta_X$ percent.

3 Reducing fine-tuning in bottom-up approach

In this section, we examine the fine-tuning problem in a bottom-up approach, where all the soft parameters are regarded as independent ones to each other in their origins. For instance, the situation that each gauge kinetic function depends on different (independent) messenger fields may result in the independent gaugino masses at the messenger scale.

In this case, the degree of fine-tuning in the model can be evaluated by the largest one Δ_X among all the fine-tuning parameters defined in Eq. (17) and written explicitly as

$$\begin{aligned}
\Delta_{M_1} &= -0.00975\hat{M}_1^{\,2} + (0.0339\hat{M}_3 + 0.00675\hat{M}_2 + 0.0136\hat{A}_t)\,\hat{M}_1,\\
\Delta_{M_2} &= -0.433\hat{M}_2^{\,2} + (0.235\hat{M}_3 + 0.00675\hat{M}_1 + 0.0840\hat{A}_t)\,\hat{M}_2,\\
\Delta_{M_3} &= 5.45\hat{M}_3^{\,2} + (0.0339\hat{M}_1 + 0.235\hat{M}_2 + 0.387\hat{A}_t)\,\hat{M}_3,\\
\Delta_{A_t} &= 0.214\hat{A}_t^{\,2} + (0.387\hat{M}_3 + 0.0840\hat{M}_2 + 0.0134\hat{M}_1)\,\hat{A}_t,
\end{aligned} \tag{19}$$

and

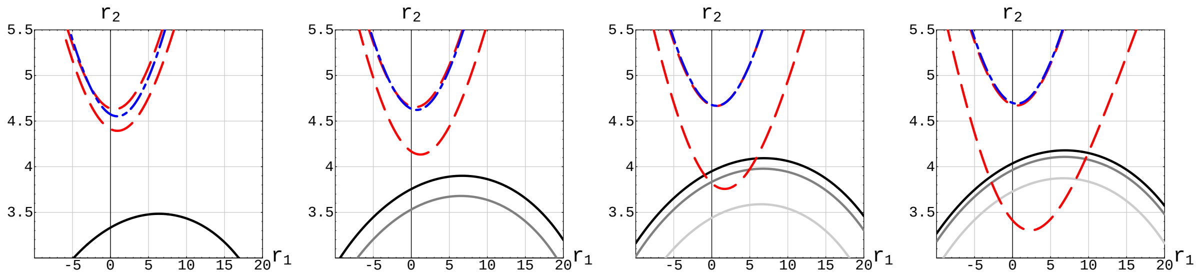
$$\Delta_\mu \;=\; -1.09\hat{\mu}^2, \tag{20}$$

where $\hat{M}_a = M_a/M_Z$, $\hat{A}_t = A_t/M_Z$ and $\hat{\mu} = \mu/M_Z$. When we require $|\Delta_\mu| \lesssim 10$, allowed values of $|\mu|$ are $|\mu| \lesssim 280$ GeV.

We easily find that Δ_{M_3} tends to be the largest among Δ_{M_a} and Δ_{A_t} for the universal gaugino masses $M_1 = M_2 = M_3 = M$ with $A_t \sim O(M_a)$. In this case, if we require the fine-tuning for M_3 to be more than 10 %, that is $\Delta_{M_3} \approx 6\hat{M}_3^{\,2} \leq 10$, the gluino mass M_3 at the GUT scale is restricted as

$$M \;\lesssim\; 120 \text{ GeV}, \qquad \text{for } \; M_1 = M_2 = M_3 = M. \tag{21}$$

This does not satisfy the Higgs mass bound (13) for $A_t(M_Z)/m_{\tilde{t}} \lesssim 1.5$. Therefore, a larger $A_t(M_Z) > 1.5\, m_{\tilde{t}}$ is inevitable as can be read off from Fig. 1. However, Eq. (10) leads to $A_t(M_Z) \sim 2.8 M_3$, while Eq. (12) results in $m_{\tilde{t}} \sim 2.2\, M_3$. Thus, we find $A_t(M_Z) > 1.5 m_{\tilde{t}}$



$M = 110$ GeV $\quad$ $M = 150$ GeV $\quad$ $M = 200$ GeV $\quad$ $M = 250$ GeV

Figure 2: Curves for $r_a = A_t/M_3 = 0$ and $m_{H_u}^2 = m_{Q_3,U_3}^2 = 0$ determined by constraints from $\Delta_M = 3.4,\ 5,\ 10$ (solid curves), $m_{h^0} \geq 114.4$ GeV (between two dashed curves) and $m_{\tilde{t}_1} \geq 95.7$ GeV (below dot-dashed curves). The parameter Δ_μ is fixed by the constraint $\Delta_M + \Delta_\mu = 1$. The solid curves are darker for the smaller Δ_M.

is impossible. On the other hand, a large value of M_3 like $M_3 = 220$ or 450 GeV in Eq. (13) leads to a large value of Δ_{M_3} like $\Delta_{M_3} = 30$ or 130. For the latter case, we need fine-tuning less than 1%.

The above argument for $M_1 = M_2 = M_3$ with $A_t \sim O(M_a)$ shows that only the possibility to reduce the fine-tuning associated to M_3 keeping $A_t \lesssim O(M_a)$ is *a departure from the universal gaugino mass condition* at the GUT scale.

Here we denote ratios of gaugino masses and A_t by r_1, r_2 and r_a as

$$(M_1,\, M_2,\, M_3) \;=\; (r_1,\, r_2,\, 1)\, M, \qquad A_t \;=\; r_a\, M, \tag{22}$$

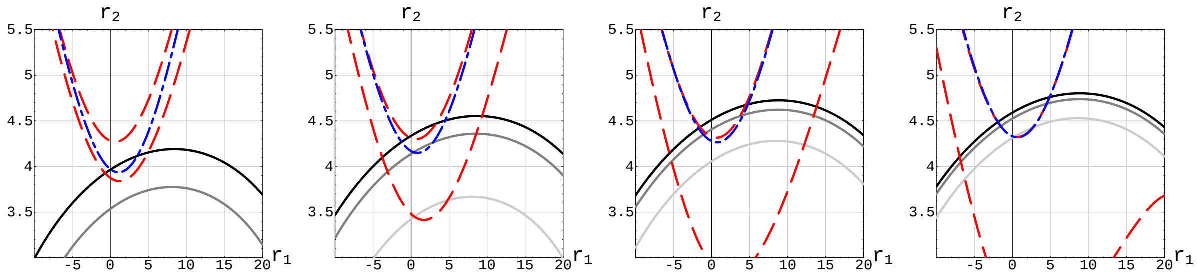
where M corresponds to the overall magnitude of soft SUSY breaking parameters. Note that we consider ratios, r_1, r_2 and r_a are free parameters independent of M in this section. Let us define Δ_M as

$$\Delta_M \;=\; \sum_{a=1}^{3} \Delta_{M_a} + \Delta_{A_t}. \tag{23}$$

Since $\Delta_\mu = 1 - \Delta_M$, we are required to obtain $\Delta_M \lesssim O(10)$ in order to avoid fine-tuning of Δ_μ, although this condition is not sufficient and small values Δ_X for $X = M_1, M_2, M_3$ and A_t are also required. In Δ_M, the dominant contribution is due to $\hat{M}_3$ as obvious from Eq. (19). The next important contribution would come from $\hat{M}_2$, because of its sign in Δ_{M_2}. Indeed, we would obtain $\Delta_M \approx 0$ for $r_2 \approx 4$ when $\hat{M}_1 = A_t = 0$. On the other hand, the $\hat{M}_1$-dependence of Δ_M would be small, because its coefficient is small. This naive estimation suggests that the parameter region around $r_2 \sim 4$ would be favorable, while a larger region for r_1 would be favorable.

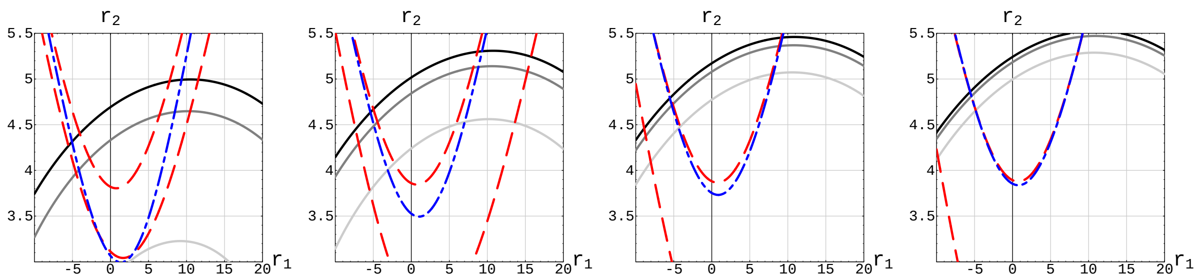
As r_2 increases, $m_{H_u}^2(M_Z)$ increases and $m_{U_3}^2(M_Z)$ decreases. For instance, in the extremal case $r_2 \to \infty$, the successful electroweak symmetry breaking would not be realized, but the color symmetry would break radiatively. Thus, the parameter r_2 as well as others is constrained by experimental bounds of the stop mass and μ and the successful realization of electroweak symmetry breaking.

Figs. 2, 3 and 4 show the contours of $\Delta_M = 3.4, 5, 10$ in $(r_1,\, r_2)$-plane for $M = 110, 150, 200$ and 250 GeV in the case of $r_a = 0,\ 1,\ 2$, respectively. The darkest and



$M = 110$ GeV $\quad M = 150$ GeV $\quad M = 200$ GeV $\quad M = 250$ GeV

Figure 3: The same curves as Fig. 2 but with $r_a = A_t/M_3 = 1$.



$M = 110$ GeV $\quad M = 150$ GeV $\quad M = 200$ GeV $\quad M = 250$ GeV

Figure 4: The same curves as Fig. 2 but with $r_a = A_t/M_3 = 2$.

darker solid lines correspond to $\Delta_M = 3.4$ and 5, respectively, while the less dark line corresponds to $\Delta_M = 10$. Above the line corresponding to $\Delta_M = 3.4$, we can not realize the successful electroweak symmetry breaking when $m_{H_u} = 0$ and $|\mu(M_Z)| \geq 94$ GeV, which corresponds to the experimental bound of chargino mass.

In these figures, we also show the regions satisfying the current Higgs and top squark mass bounds [23], $m_h \geq 114.4$ GeV and $m_{\tilde{t}_1} \geq 95.7$ GeV, respectively, where $m^2_{\tilde{t}_1}$ ($m^2_{\tilde{t}_2}$) is the smaller (larger) eigenvalue of the top squark mass-square matrix

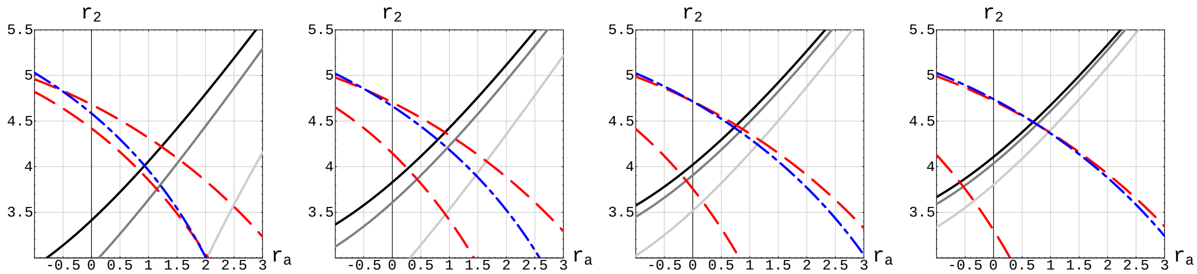
$$M^2_{\tilde{t}} \;=\; \begin{pmatrix} m^2_{Q_3}(M_Z) + m_t^2 + \delta_Q & m_t \tilde{A}_t \\ m_t \tilde{A}_t & m^2_{U_3}(M_Z) + m_t^2 + \delta_U \end{pmatrix},$$

with $\delta_Q = (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos(2\beta)M_Z^2$, $\delta_U = \frac{2}{3}\sin^2\theta_W\cos(2\beta)M_Z^2$ and $\sin^2\theta_W = 1 - M_W^2/M_Z^2$. We obtain $m_h \geq 114.4$ GeV between two dashed lines, while we obtain $m_{\tilde{t}_1} \geq 95.7$ GeV below the dot-dashed line, which is close to the upper dashed line in several cases. Figs. 5, 6 show the same contours as Figs. 2, 3 and 4 in (r_a, r_2)-plane for $M = 110, 150, 200$ and 250 GeV in the case of $r_1 = 2$, 7.13, respectively. The ratio $r_1 = 7.13$ is a solution of $M_1(M_Z) = M_3(M_Z)$, i.e., the unification of the bino and the gluino mass at the EW scale.

From Figs. 2, 3, 4, 5 and 6, we find that the Higgs mass bound as well as the top squark one is satisfied within $|\Delta_M| \leq 10$ for the ratios r_1, r_2 and r_a inside the region,

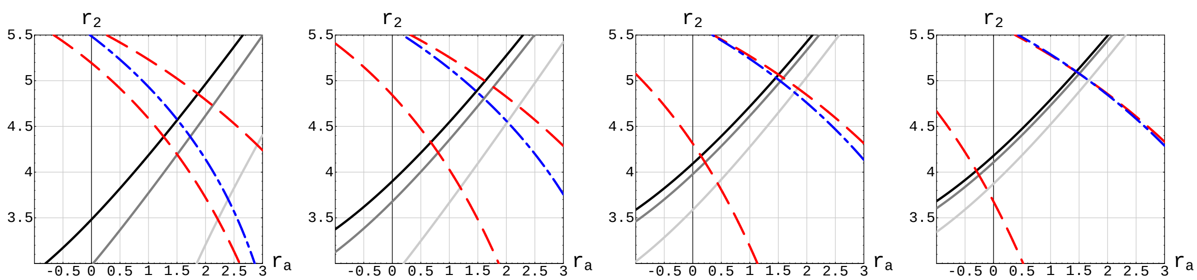
$$-10 \;\lesssim\; r_1 \;\lesssim\; 15, \qquad 3.5 \;\lesssim\; r_2 \;\lesssim 5.5, \qquad 0 \;\lesssim\; r_a \;\lesssim\; 2, \tag{24}$$

when the SUSY breaking scale M varies from 110 GeV to 200 GeV. Within this region,



$M = 110$ GeV $M = 150$ GeV $M = 200$ GeV $M = 250$ GeV

Figure 5: Curves for $r_1 = M_1/M_3 = 2$ and $m^2_{H_u} = m^2_{Q_3,U_3} = 0$ determined by constraints from $\Delta_M = 3.4,\ 5,\ 10$ (solid curves), $m_{h^0} \geq 114.4$ GeV (between two dashed curves) and $m_{\tilde{t}_1} \geq 95.7$ GeV (below dot-dashed curves). The parameter Δ_μ is fixed by the constraint $\Delta_M + \Delta_\mu = 1$. The solid curves are more dark for the smaller Δ_M.



$M = 110$ GeV $M = 150$ GeV $M = 200$ GeV $M = 250$ GeV

Figure 6: The same curves as Fig. 5 but with $r_1(M_Z) = M_1(M_Z)/M_3(M_Z) = 1$ ($r_1 = 7.13$).

the fine-tuning parameter Δ_{M_3} (contained in Δ_M) given by Eq. (19) is estimated as

$$5.5\,(M/M_Z)^2 \ \lesssim\ \Delta_{M_3}\ \lesssim\ 8\,(M/M_Z)^2.$$

Thus, in order the fine-tuning associated to M_3 to be more than 10 %, the SUSY breaking scale is restricted by

$$M \ \lesssim\ 110\text{ - }120 \text{ GeV}. \tag{25}$$

In Fig. 2 with $r_a = 0$, we find that there is no allowed region for $M \leq 150$ GeV. Then, from Eq. (25), we conclude that the non-vanishing A-term at the GUT scale, $r_a \neq 0$, is required for reducing the fine-tuning above 10 % order.

In Table 1, we show some mass spectra for $M = 110$ GeV (as well as for $M = 200$ GeV which will be explained later) at some typical points of (r_1, r_2, r_a) which lead to $\Delta_M \sim 5$, i.e., about 20 % tuning in terms of M. For $M = 110$ GeV which is the marginal value of the condition (25), we find $\Delta_{M_3} \sim 10$ and $A_t(M_Z)/m_{\tilde{t}} \sim 2$ are realized for $r_a = 1$ and $r_a = 2$. These two are distinguished by the masses of the bino and the lighter top squark at the M_Z scale. The wino mass is similar to the gluino mass for $r_a = 1$, and is larger than it for $r_a = 2$ at the M_Z scale. This is because the larger value of r_2 is preferred for the larger value of r_a in Fig. 2 - Fig. 6.

M (GeV)	110	110	200	200	200
r_a	1	2	0	1	2
$(r_1,\ r_2)$	(3, 4.0)	(10, 4.8)	(2, 3.9)	(5, 4.6)	(10, 5.4)
Δ_M	3.8	4.3	5.1	4.7	4.4
Δ_{M_3}	10.1	11.3	31.2	34.4	38.0
$A_t(M_Z)/m_{\tilde{t}}$	2.0	1.9	1.6	2.4	2.2
$M_3(M_Z)$ (GeV)	321	321	583	583	583
$M_2(M_Z)$ (GeV)	361	433	640	755	886
$M_1(M_Z)$ (GeV)	135	450	164	409	818
$\mu(M_Z)$ (GeV)	108	117	130	125	120
$m_{\tilde{t}_2}$ (GeV)	436	468	714	764	820
$m_{\tilde{t}_1}$ (GeV)	202	131	247	133	186
$m_{h,\max}$ (GeV)	115	115	115	120	120

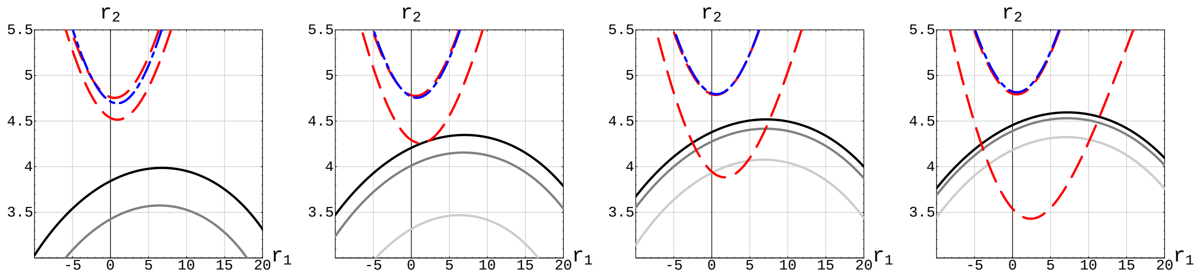
Table 1: The mass spectra for $M = 110$ and 200 GeV at some typical points of $(r_1,\, r_2,\, r_a)$ which lead to $\Delta_M \sim 5$ (20 % tuning).

Finally in this section, we summarize the discussions above. If all the soft parameters (as well as the μ-term) at the GUT scale are independent to each other in their origins, the degree of fine-tuning in the model is almost determined by Δ_{M_3}. A numerical evaluation indicates that only the possibility for relaxing the fine-tuning above 10 % order ($\Delta_{M_3} \lesssim 10$) resides in the case of i) non-universal gaugino masses with the ratio inside the region (24), ii) a non-vanishing A-term at the GUT scale, $A_t > 0$, and iii) a considerably low SUSY breaking scale (25).

4 Fine-tuning with fixed ratios

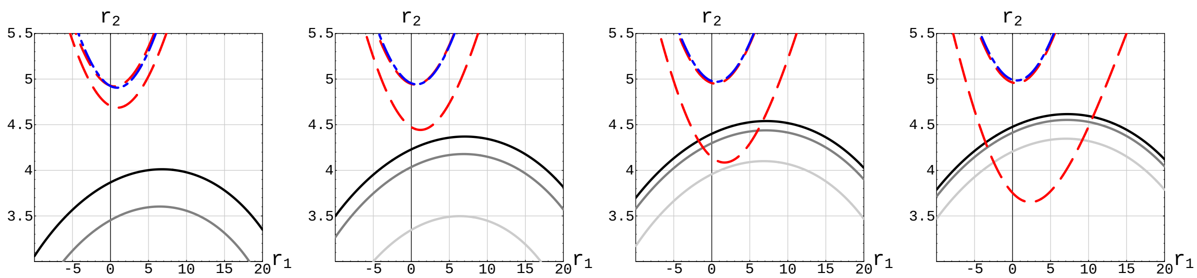
It is reasonable enough to consider the situation that some or all of the soft SUSY breaking parameters share a common mass scale M, and the ratios between them are determined by some dimension less constants and/or geometrical numbers such as beta function coefficients, modular weights, and so on. Indeed, ratios of soft SUSY breaking parameters are fixed as certain values in each model, e.g. in moduli mediation, anomaly mediation, gauge messenger model and so on. In this case, we do not need to worry about all of the fine-tuning parameters (19), and the degree of fine-tuning in the model is represented by only Δ_M.

In this section, we reexamine the discussions in the previous section, by assuming that the ratio r_1, r_2 and r_a in Eq. (22) is fixed to some numbers by the UV theory. In this case, the remaining fine-tuning parameters are Δ_M and Δ_μ given by Eqs. (23) and (20), respectively. In other words, we worry about the sensitivity of the Z-boson mass to only the common SUSY breaking scale M and the SUSY mass scale μ. The Δ_{M_3} is a meaningless parameter in this sense, and thus the SUSY breaking scale M is released from the previous upper bounds (25) or (21). The numerical results in Fig. 2-Fig. 6 show that $M \sim 200$ GeV possesses the widest allowed region of the ratios r_1, r_2 and r_a. This



$M = 110$ GeV $\quad M = 150$ GeV $\quad M = 200$ GeV $\quad M = 250$ GeV

Figure 7: The same curves as Fig. 2 but with $m_{H_u}^2 = -M^2$.



$M = 110$ GeV $\quad M = 150$ GeV $\quad M = 200$ GeV $\quad M = 250$ GeV

Figure 8: The same curves as Fig. 2 but with $m_{Q_3,U_3}^2 = M^2$.

is because the smaller M results in a smaller allowed region for the Higgs and the top squark mass bounds, while the region where $\Delta_M \leq 10$ becomes narrower for the larger M. These opposite tendencies are balanced at $M \sim 200$ GeV.

It is remarkable that the fine-tuning can be completely improved in this case. For some values of r_1, r_2 and r_a inside (24), the fine-tuning parameter Δ_M can be of $O(1)$, and then Δ_μ is also of $O(1)$ from Eq. (18). Note that Δ_{M_3} is still large $\Delta_{M_3} \gg 1$ for $M > 120$ GeV. The point is, however, now the fine-tuning parameter is not Δ_{M_3} but the total sum $\Delta_M \sim O(1)$, where a cancellation occurs between Δ_{M_3} and $\Delta_{M_{1,2},A_t}$.

At any rate, irrespective of whether we worry about the fine-tuning parameter Δ_{M_3} or not, we can obtain $\Delta_M \sim O(1)$ in the region (24) and then $\Delta_\mu \sim O(1)$. This implies the Z-boson mass is insensitive to not only the SUSY breaking scale M but also the SUSY mass scale μ. The small Δ_μ corresponds to the small value of μ itself. It can be even the marginal value to the current chargino mass bound. The small Higgsino mass is a general consequence of reduced fine-tuning associated to the μ-parameter.

What the favored region of the ratios (24) indicates? First, this region is mostly close to the minimum of $m_{\tilde{t}}$ in terms of $A_t(M_Z)/m_{\tilde{t}}$ in Fig. 1, that is the large top squark mixing case [11, 14]. Second, the favored ratios between gaugino masses may be explained as follows. The region (24) corresponds to

$$-1.4 \lesssim r_1(M_Z) \lesssim 2.1, \quad 1.0 \lesssim r_2(M_Z) \lesssim 1.4, \tag{26}$$

where

$$r_1(M_Z) = M_1(M_Z)/M_3(M_Z) = 0.14\, r_1,$$

$$r_2(M_Z) \;=\; M_2(M_Z)/M_3(M_Z) \;=\; 0.28\, r_2, \tag{27}$$

are the gaugino mass ratios at the Z-boson mass scale. Favorable region of $r_2(M_Z)$ is rather wide, e.g. $\Delta r_2/r_2(M_Z) = O(0.1)$, where $r_2(M_Z) = 1.2$ and $\Delta r_2(M_Z) = 0.2$. We have much wider favorable region for $r_1(M_Z)$. That is important from the viewpoint of model building, because that allows 10% uncertainty for an explicit model. The ratio $r_2(M_Z) \approx 1$ indicates the unification of the wino and the gluino masses at the EW scale. Then the reduced fine-tuning can be explained in the terminology of the so-called mirage mediation [9] of SUSY breaking. The mirage unification of the gaugino masses at the EW scale [9, 10] implies that the large logarithmic correction (2) to the $m_{H_u}^2$ is completely canceled at the EW scale due to the special boundary conditions at the GUT scale as a consequence of the mixed modulus-anomaly mediation[2]. The range of the ratios (24) includes this type of boundary conditions as the central values.

However, from (26) we find that, in order to reduce the fine-tuning, it is not necessary that all the gaugino masses are unified at the EW scale as in the mirage mediation models. The important one is the wino/gluino mass ratio, and we have a wider choice for the value of bino/gluino mass ratio as long as the fine-tuning is concerned. Inversely, the relaxed fine-tuning may predict the unification of the wino and gluino masses at the EW scale, but not the bino-gluino unification.

In Table 1, the mass spectra for $M = 200$ GeV are shown at some typical points of (r_1, r_2, r_a) which lead to $\Delta_M \sim 5$, i.e., about 20 % tuning in terms of M. The vanishing A_t at the GUT scale $r_a = 0$ is possible for $M = 200$ GeV as well as $r_a = 1, 2$. In the case of $r_a = 0$, the large $A_t(M_Z)/m_{\tilde{t}} \sim O(1)$ at the Z-boson mass scale is generated radiatively. The three cases $r_a = 0, 1, 2$ are most likely distinguished by the mass of the bino at the M_Z scale. This is due to the fact that the larger r_a prefers the larger r_1 for $\Delta_M \leq 5$ as can be seen by comparing Fig. 2 - Fig. 4. The wino mass is similar to the gluino mass for $r_a = 0$, and is larger than it for $r_a = 1, 2$ at the M_Z scale. Because we are now taking such a stance that the gaugino masses are not independent in their origins, the value of Δ_{M_3} is meaningless, although it is shown in Table 1 for the purpose of reference.

So far, we have considered the case with vanishing soft scalar masses, $m_{H_u} = m_{Q_3} = m_{U_3} = 0$. Here we comment on effects due to non-vanishing soft scalar masses. First, let us evaluate effects due to non-vanishing value of the Higgs soft scalar mass m_{H_u}. Its effect on stop masses is small. That implies that the lightest Higgs mass m_h and stop masses $m_{\tilde{t}}$ would not change significantly even when we vary m_{H_u} in the region with $|m_{H_u}^2| \lesssim O(M^2)$. A significant effect appears only in $m_{H_u}^2(M_Z)$, and such effect can be understood as 'renormalization' (15). That is, the favorable region with small Δ_M shifts toward the region with larger (smaller) r_2, when m_{H_u} becomes negative (positive). Fig. 7 shows the case with $m_{H_u}^2 = -M^2$. Next, we comment on effects due to non-vanishing values of m_{Q_3} and m_{U_3}. Their effects on Δ_M are almost opposite to the above effect of m_{H_u}, because their signs are opposite in Eq. (7). The small Δ_M region shifts toward the region with larger (smaller) r_2, when $m_{Q_3} = m_{U_3}$ becomes positive (negative). Furthermore,

[2] In the flux compactification models [24], the mirage unification scale is determined by the modulus/anomaly ratio of SUSY breaking mediation [18], which depends on the dilaton-modulus mixing ratios in the nonperturbative superpotential [25, 27] as well as how we uplift the AdS minimum to dS one [26, 27, 28].

they also affect on the lightest Higgs mass m_h and stop masses $m_{\tilde{t}}$. Then, totally the favorable region shifts slightly when we vary $m_{Q_3} = m_{U_3}$, but the wideness of favorable region does not change drastically. Fig. 8 shows the case with $m^2_{Q_3,U_3} = M^2$.

5 Conclusions

We studied the fine-tuning problem between the soft SUSY breaking parameters and the μ-term for the successful electroweak symmetry breaking in the MSSM. The bottom-up considerations lead us to *the non-universal gaugino masses* at the GUT scale as a necessary condition for reducing the fine-tuning above 10 % order, if all the soft parameters are regarded as independent ones to each other in their origins and no tachyonic super-particles are assumed at the GUT scale. In this case, the small gluino mass $M_3 \lesssim 120$ GeV and the non-vanishing A-terms $A_t > 0$ at the GUT scale is required from $\Delta_{M_3} \lesssim 10$.

On the other hand, if the soft SUSY breaking parameters share a common mass scale M with the fixed ratios by the UV theory, each fine-tuning parameter such as Δ_{M_3} does not make any sense. Only the total one such as $\Delta_M = \sum_{a=1}^{3} \Delta_{M_a} + \Delta_{A_t}$ as well as the SUSY parameter Δ_μ represents the degree of fine-tuning in the model. In this case, the above upper-bound on M_3 disappears, and then we find the fine-tuning can be completely improved in some models of non-universal gaugino masses. A numerical evaluation shows that the model with the gluino mass $M_3 \sim 200$ GeV at the GUT scale has the widest allowed range of $r_1 = M_1/M_3$, $r_2 = M_2/M_3$ and $r_a = A_t/M_3$. In this case of the least fine-tuning, even the vanishing A_t at the GUT scale is possible and a relatively large $A_t(M_Z)/m_{\tilde{t}} > 1.5$ at the Z-boson mass scale is generated radiatively.

In both the above approaches, the non-universal gaugino mass conditions, especially, $M_2 \approx 4M_3$ at the GUT scale is the key to improve the fine-tuning. This implies the wino and gluino degeneracy at the weak scale. Another implication is a smaller Higgsino mass due to the reduced or eliminated fine-tuning $\Delta_M \leq 10$ accompanying $|\Delta_\mu| \leq 10$. The bino mass M_1 at the GUT scale is less constrained from our discussions of fine-tuning. This fact implies that the EW mirage-unification model [9, 10], where all the gaugino masses are unified at the EW scale, can be deformed such that only the wino and gluino masses are unified, keeping the absence of fine-tuning. In other words, the $U(1)_Y$ gauge kinetic function can have a different origin from the other ones for $SU(3)_C$ and $SU(2)_L$. It would be important to study model building at high energy scale, extending the low-energy scale mirage [9, 10]. We would study elsewhere explicit construction of such partial mirage model, where only the gluino and wino masses are degenerate around M_Z. A negative value of m_{H_u} makes the favorable region wider, and larger value of M_2/M_3 becomes favorable. On the other hand, when we vary stop masses m_{Q_3,U_3}, the situation does not change drastically.

Our favorable value of μ is small. For example we have $|\mu| \lesssim 280$ GeV, when we require $\Delta_\mu \lesssim 10$. In addition, the bino mass M_1 can vary in a quite wide range. This aspect would be interesting from the viewpoint of dark matter candidate.

We have concentrated to the Higgs sector and the electroweak symmetry breaking, to which only gaugino masses, stop masses and Higgs masses are relevant. Other mass parameters are irrelevant to our discussion, that is, they can be more model-dependent.

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